Appendix D

Infiltration Calculations

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Central Facilities Area Sewage Treatment Plant Drainfield (CFA-08) Protective Cover Infiltration Study

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5. Summary:

A hydrological modeling study of the existing Central Facilities Area (CFA) drainfield site and a preliminary cover design was performed to demonstrate that the cover will reduce deep percolation within the drainfield. Three one-dimensional profiles were modeled. The first profile was a 162-cm deep homogeneous control profile consisting of the sandy loam present at the surface of the CFA-08 drainfield. The second profile was 183 cm (6 ft) deep and included a natural gravel/sand stratum below 60 cm (2 ft) of the native sandy loam. This profile was simulated to assess whether the natural layering at the CFA-08 drainfield is behaving as a natural capillary barrier system. The third profile represented the preliminary soil cover design. The cover profile was simulated as 122 cm (4 ft) of silty clay from the Idaho National Engineering and Environmental Laboratory's (INEEL's) Rye Grass Flat or loam from the Lincoln Boulevard Borrow Source, 10 cm (4 in.) of gravel, and 30 cm (1 ft) of cobbles. The particle size distribution of the existing soil and proposed cover material were used to estimate the native soil and cover material hydrological properties.

The results of this study indicate that an engineered capillary barrier cap will significantly reduce deep percolation at the CFA-08 drainfield site from the current amount. The simulations indicate the aquifer recharge rate (5 cm/year) at the drainfield is greater than the INEEL average (1 cm/year), and placement of a barrier cap will reduce this value to 0.5 cm/year or less.

6. Review (R) and Approval (A) and Acceptance (Ac) Signatures: Steve Davies, Melanie Snedden, Pete Martian
(See instructions for definitions of terms and significance of signatures.)

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CONTENTS

FIGURES

TABLES

ACRONYMS

CFA Central Facilities Area

INEEL Idaho National Engineering and Environmental Laboratory

PET potential evapotranspiration

Central Facilities Area Sewage Treatment Plant Drainfield (CFA-08) Protective Cover Infiltration Study

1. INTRODUCTION

The Central Facilities Area (CFA) sewage treatment plant CFA-08 drainfield has been used for disposal of sewage plant effluent from 1944 through 1995. During the period 1950–1995, a laundry, which cleaned low-level radionuclides from protective clothing, discharged radionuclide residues to the sewage treatment plant and drainfield. As a result of the laundry operations, the soil in the drainfield is contaminated with cesium-137. The Waste Area Group 4 remedial investigation/feasibility study determined that the cesium-137 contamination in the drainfield poses a potential human health risk, and the Operable Unit 4-13 Record of Decision decided constructing an engineered soil cover is needed for remediation. The cover will be a capillary/biobarrier-type engineered cover consisting of soil overlying layers of cobble rock and gravel. The cobble rock and soil layering will prevent intrusion of plant and animals, reduce deep percolation, and prevent wind dispersal of the contaminated soil.

A hydrological study has been performed to demonstrate that the preliminary cover design will significantly reduce meteorological infiltration within the drainfield. The study was performed by numerical simulation of the water balance in the preliminary cover design and in the existing soil at the CFA-08 drainfield site.

The human health risk for the CFA-08 drainfield is from current and future occupational workers and future resident exposure to external radiation from Cs-137. Radioactive decay will reduce the Cs-137 radiation exposure risk to an acceptable level in 189 years, which is the period over which the cover will need to function.

2. BARRIER FIELD STUDIES AT THE INEEL

The CFA-08 drainfield cover will reduce infiltration by utilizing a soil-plant cover system and a capillary-biobarrier. The proposed cover will function by intercepting and storing precipitation until it is returned to the atmosphere via evapotranspiration. The low matric potential in the fine-textured material above the capillary/biobarrier will hold water against gravity until vegetation and evaporation removes the available soil moisture. Covers incorporating capillary/ biobarriers can fail if insufficient water storage exists in the soil above the capillary/biobarrier layer. Water will only remain in the fine-textured material while the material remains unsaturated. At this time, the upward matric potential gradient due to capillarity becomes less than the unit gradient due to gravity and the capillary barrier will fail, allowing water to drain through the cap. Several studies have been performed at the Idaho National Engineering and Environmental Laboratory (INEEL) to determine the ability of soil plant cover systems and covers utilizing capillary/biobarriers to store soil moisture during times of low potential evapotranspiration and high infiltration and return the moisture to the atmosphere during times of high potential evapotranspiration (Anderson, Shumar, and Toft 1987; Anderson et al. 1991 and 1993; Porro and Keck 1998; and Porro 2000).

The studies performed by Anderson et al. examined the capacity of perennial plants to deplete soil moisture and the storage capacity of the soil. Ten waste trenches were constructed at the INEEL Experimental Field Station in 1983. Each trench was 3 m wide, 10.7 m long, and 2.4 m deep and was instrumented with neutron probe access holes to measure soil moisture. The test trenches were planted with four perennial plant species: wyoming sage brush, crested wheatgrass, stream bank wheatgrass, and great basin wild rye. Two of the test trenches were left bare to evaluate moisture loss from evaporation alone.

The soil moisture was measured from 1984 through 1989 and included a period during which the ambient precipitation was augmented with irrigation to represent a very high precipitation year. The experimental results indicated that any of the four plant species could extract all the available soil water, including that from an exceptionally high precipitation year. In contrast to the vegetated test trenches, the bare test trenches retained a high moisture content and experienced substantial drainage. The study also estimated the water storage capacity of the test trench soil to be approximately 17% by volume and the minimum thickness needed to store precipitation during times of low potential evapotranspiration to be approximately 1.6 m.

The studies performed by Porro and Keck (1998) and Porro (2000) investigated the performance of two engineered barrier designs at the INEEL under extreme infiltration conditions. The purpose of the experiment was to determine the amount of time needed for an engineered barrier to recover enough water storage capacity from saturated conditions to begin preventing deep percolation. The first design consisted of a thick soil type cover and the second design incorporated a capillary/biobarrier. The Engineered Barriers Test Facility was constructed in the spring of 1996. Five 3-m wide by 3-m long by 3-m deep cells were placed on either side of an enclosed access trench. The cells were instrumented to measure moisture content and matric potential. The cells were also equipped with tipping buckets and pressure transducers in the drainage sumps to measure drainage rates.

The test plots were subject to ambient weather conditions after their construction until the summer of 1997. At this time, wetting tests were conducted by applying irrigation until drainage was observed. The amount of water applied was approximately 50 cm over a 3-day period. The drainage resulting from the wetting test in the capillary/biobarrier test cells had a smaller magnitude and shorter duration than the thick soil test cells. A similar drainage pattern was seen the following spring. Drainage from the thick soil test cells represented 2/3 of the total winter precipitation, while drainage from the capillary/biobarrier represented 1/3 of the total winter precipitation. During the second spring and subsequent springs following the wetting test, substantial drainage was only seen from the thick soil test cells and was decreasing each year. The capillary/biobarrier test cells had recovered enough water storage capacity within a year and a half to prevent further deep percolation.

In conclusion, the studies conducted by Anderson et al. and Porro and Keck indicated that a cover design incorporating either soil plant cover or a capillary/biobarrier system will effectively stop deep percolation at the INEEL. The proposed CFA-08 cover will incorporate both features in its design and should perform as well or better than the covers studied.

3. NUMERICAL MODEL

The UNSAT-H Version 2.05 (Fayer and Jones 1990) model was chosen for the simulation study because it numerically solves the general partial differential equation governing unsaturated fluid flow in porous media without using any significant limiting assumptions. The model is applicable to most unsaturated conditions and is especially well suited for semiarid locations. The UNSAT-H model is designed to simulate the dynamics of water movement through the vadose zone as a function of meteorologic conditions and soil hydraulic properties. UNSAT-H Version 2.0 is an enhanced version of UNSAT-H 1.0. Version 1.0 simulates the processes of infiltration, redistribution, drainage, and evapotranspiration and uses the potential evapotranspiration (PET) concept. Version 2.0 additionally includes the options to calculate soil heat transfer coupled with water flow, surface-energy balance, and actual evaporation.

The model is written in FORTRAN 77 and consists of three main programs: (1) DATAINH, a preprocessor; (2) UNSAT-H, the flow simulator; and (3) DATAOUT, a post-processor. For simple problems, the model runs efficiently on a personal computer. However, for cases with complex stratigraphy, the model may require a scientific workstation or faster computer. The model was verified and benchmark tested by Baca and Magnuson (1990) and has successfully been applied to simulate moisture movement at several semiarid locations (Fayer, Rockhold, and Campbell 1992; Baca, Nguyen, and Martian 1992; and Martian and Magnuson 1994).

3.1 Model Theoretical Background

Flow in unsaturated porous media is often described using Richards' equation (Richards 1931). The UNSAT-H model solves an extended, one-dimensional form of Richards' equation that includes both liquid- and vapor-phase water movement. To model soil heat transfer, the model solves the advection-diffusion equation. The extended form of Richards' equation, as implemented in the model, is

$$C(h)\frac{\partial h}{\partial t}=\frac{-\partial}{\partial z}\left[K_T(h)\frac{-\partial h}{\partial z}+K_L(h)+q_{vT}\right]-S(z,t) \qquad (1)$$

where

z = depth

$S(z,t)$ = evaportranspiration sink term

q_{vT} = thermal vapor flux density

K_T = total hydraulic conductivity; $K_T=K_L+K_{vh}$

K_L = isothermal vapor conductivity

$C(h)$ = slope of soil moisture curve; $\partial\theta/\partial h$.

The governing equations are solved using an iterative finite difference approximation with a Crank-Nicholson method for the time derivative. The finite difference technique replaces the partial derivatives with a quotient of two finite differences. The end result of using finite differences is that the partial differential equation is approximated by a series of algebraic equations, which are solved simultaneously.

To solve Richard's equation, UNSAT-H requires parameterization of the moisture characteristic and hydraulic conductivity curves. UNSAT-H contains four options for describing these soil hydraulic properties: polynomials, Haverkamp functions, Brooks-Corey functions, and van Genuchten functions. The van Genuchten equation was used for this study.

UNSAT-H permits the user to select several boundary conditions. The lower boundary condition can be a unit gradient, constant head, specified flux, or zero flux. The upper boundary condition can be either a flux or a constant head. When the flux option is selected, the upper boundary condition can be a function of meteorologic conditions and alternates between a flux and a constant head or a specified flux. Initially, during periods of infiltration or evaporation, the boundary is a flux. However, if the value at the surface node becomes less than a minimum suction head (saturated conditions) during infiltration, or if the surface node exceeds a maximum value (unnaturally dry conditions) during evaporation, the upper boundary becomes a constant head until conditions revert to normal. If the surface node becomes less than a minimum, the minimum value can either be calculated internally from relative humidity or specified by the user.

Within UNSAT-H, evaporation is calculated either by an energy balance at the soil surface when the heat transfer option is selected or by the PET concept. The UNSAT-H model does not directly calculate run-off. However, if the flux of meteoric water into the surface exceeds the infiltration capacity, the excess water is assumed to be lost to run-off.

4. SIMULATION PROFILES

Three one-dimensional profiles were modeled. The first profile was a 162-cm (5.3-ft) deep homogeneous control profile consisting of the sandy loam present at the surface of the CFA-08 drainfield. The second profile was 183 cm (6 ft) deep and included a natural gravel/sand stratum below 60 cm (2 ft) of the native sandy loam. This profile was simulated to assess whether the natural layering at the CFA-08 drainfield is behaving as a natural capillary barrier system. If the contrast in hydraulic properties between the sandy loam and gravel/sand layer below is sufficient, the infiltration pattern would be very different than through a homogeneous profile. The third profile represented the preliminary soil cover design. The cover profile is comprised of 122 cm (4 ft) of silty clay from the INEEL 's Rye Grass Flat or loam from the Lincoln Boulevard Borrow Source, 10 cm (4 in.) of gravel, and 30 cm (1 ft) of cobbles. The preliminary cover design also included an additional 10 cm of gravel under the cobbles. The additional gravel was not simulated, because the additional capillary barrier material would not change the simulations results but would increase the computational burden. The three simulated profiles are illustrated in Figure 1.

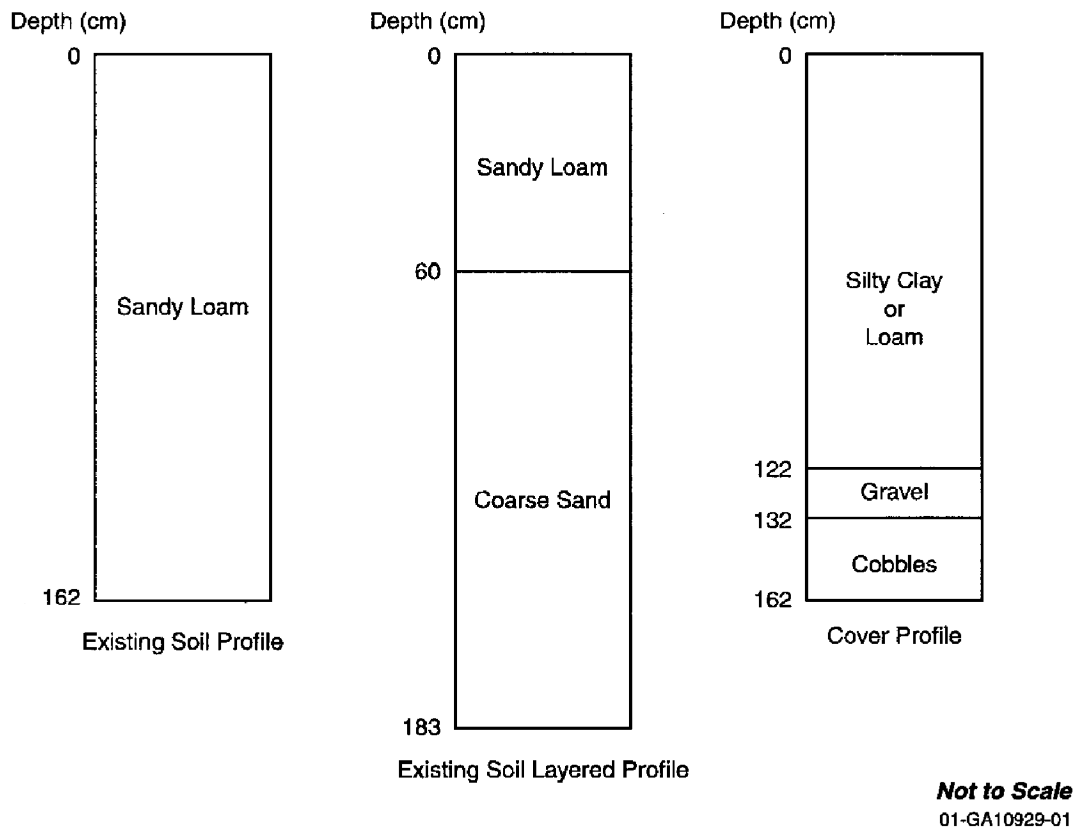

Figure 1. Simulation profiles.

5. SOIL HYDRAULIC PROPERTIES

The soils near the CFA-08 drainfield are sandy loams or loams to a depth of about 14 to 17 in. with interbedded gravel and sand deeper in the vertical profile. The average sand, silt, and clay percentage of soil samples taken nearest the CFA-08 drainfield is 73.0% sand, 19.9% silt, and 7.1% clay. This distribution of particle sizes places the soil in the sandy loam classification. The soil particle size distribution was not available for soil at depths greater than 17 in. The soil at this depth is assumed to be an unscreened mix of sand and gravel that behaves hydraulically as a coarse sand.

The soil currently proposed for use in the engineered cover is from the Rye Grass Flats playa located southwest of the Power Burst Facility or the Lincoln Boulevard Borrow Source. Particle size analysis of soil samples taken from the top 3.5 ft at the Rye Grass Flats area indicates that the particle size distribution is 12.4% sand, 44.6% silt, and 43.0% clay. This particle size distribution places the soil in the silty clay class. Particle size analysis of soil samples taken from the overburden at the Lincoln Boulevard Borrow Source indicates that the particle size distribution is 38.6% sand, 35.4% silt, and 26.1% clay. This particle size distribution places the soil in the loam class.

The van Genuchten models for soil/water retention and unsaturated hydraulic conductivity were used in the simulations. The van Genuchten model uses four parameters: (1) the alpha parameter, which is related to the inverse air entry potential; (2) the n parameter, which is related to the pore size distribution; (3) the porosity; and (4) the residual water content. Representative van Genuchten model parameters for the CFA-08 sandy loam and Rye Grass Flat silty clay were obtained from Carsel and Parrish (1988). Carsel and Parrish presented a method for developing probability density functions of the van Genuchten model parameters from the soil's particle size distribution. Although the parameters taken from Carsel and Parrish are appropriate for preliminary calculations, they should not be used in a final analysis of cover performance. Laboratory testing to determine the unsaturated characteristics of the proposed barrier soil should be performed and used in the infiltration modeling.

Hydraulic parameters for the filter gravel were taken from Fayer, Rockhold, and Campbell (1992). Fayer, Rockhold, and Campbell used a capillary pore model to calculate moisture contents for different tensions up to 0.27 cm. For tensions exceeding 0.27 cm, moisture contents were estimated. Hydraulic properties for the coarse sand were taken from Carsel and Parrish (1988). Because no experimental data were available for porous media similar to the cobbles, the author relied on his experience to estimate the hydraulic properties. The values were assigned to permit rapid drainage of the cobble layer. Table 1 presents the estimated van Genuchten soil water retention model parameters.

Table 1. Soil hydraulic properties.

Soil	K_s (cm/hr)	θ_S	θ_r	α (1/cm)	N
Sandy Loam	4.42	0.41	0.065	0.075	1.89
Silty Clay	0.02	0.36	0.070	0.005	1.09
Loam	1.04	0.43	0.078	0.036	1.56
Coarse Sand	29.7	0.43	0.045	0.145	2.68
Gravel	1,260.	0.42	0.005	4.93	2.19
Cobbles	3,600.	0.40	0.005	10.	3.0

5.1 Boundary and Initial Conditions

The simulation boundary conditions were an atmospheric flux at the surface and free drainage at the bottom. Meteorological records from an infiltration study at the Subsurface Disposal Area (Martian 1995) were used in this study. The records consisted of daily values for maximum air temperature, minimum air temperature, dewpoint temperature, solar radiation, average wind speed, and daily precipitation. The meteorological data represented the period January 1950 through December 1994 and the model simulated each individual day during this period. The period 1950 through 1952 was used to obtain initial conditions for the final 1952–1994 simulation period. This method selected a time far enough in advance of the simulation period of interest so that the water content in the two profiles would be in quasi-equilibrium with meteorologic conditions when the simulation period of interest occurred. Furthermore, the first year of the simulation (1950) used initial conditions from 2 years of simulating a representative average year of precipitation. This year was 1981, which had a total precipitation of 8.5 in. The average precipitation of the 1950 through 1994 period was 8.45 in. Table 2 provides the annual precipitation for each simulation year.

Table 2. Simulation period annual precipitation.

Year	Annual Preciptation (in.)	Year	Annual Preciptation (in.)	Year	Annual Preciptation (in.)	Year	Annual Preciptation (in.)
1950	4.40	1951	7.37	1952	5.73	1953	5.49
1954	7.41	1955	6.91	1956	5.78	1957	12.29
1958	7.25	1959	7.06	1960	9.17	1961	9.72
1962	10.74	1963	13.44	1964	12.64	1965	9.58
1966	4.14	1967	7.97	1968	12.74	1969	9.41
1970	7.91	1971	10.64	1972	8.34	1973	9.96
1974	8.12	1975	10.04	1976	7.87	1977	5.85
1978	7.09	1979	8.65	1980	10.24	1981	8.50
1982	8.68	1983	12.00	1984	11.34	1985	8.94
1986	12.99	1987	7.75	1988	3.67	1989	8.40
1990	6.68	1991	8.72	1992	4.01	1993	9.96
1994	4.87	—	—	—	—	—	—

Martian (1995) modified the daily precipitation records collected at the CFA weather station to account for snow accumulation and melting following the method outlined in Magnuson (1993). The results of this modification were to concentrate winter precipitation into a short period of snowmelt each spring.

Martian (1995) also modified the daily potential evapotranspiration calculated by the UNSAT-H model to account for periods when the ground surface is frozen and covered with snow. The snow cover will prevent most evaporation from occurring by insulating the ground from wind and solar radiation; as the ground freezes, the effective porosity and hydraulic conductivity can be reduced by any remaining moisture freezing in the soil pores. This reduces evaporation by limiting the amount of soil water that can move toward the soil surface. Finally, most vegetation becomes dormant during the winter months, further decreasing evapotranspiration. The combination of the above processes effectively stops most evapotranspiration during the winter season. This approach was also used in this infiltration study.

The simulation initial conditions were established starting with saturated conditions and simulating 4 concurrent years using the following meteorological data: year 1 = 1981 data, year 2 = 1981 data, year 3 = 1950 data, year 4 = 1951 data.

The hydrological study presented in this report needs to demonstrate that the biocapillary barrier will reduce infiltration from that which would occur through the existing soil at the CFA drainfield. Under "worst case" hydrological conditions, the barrier should still reduce infiltration from that occurring in the existing soil profiles, because the barrier will still intercept, store, and return to the atmosphere a larger fraction of the worst case precipitation than that returned by the existing soil profile. The capillary barrier would allow drainage equal to the native soil only if the worst case precipitation results in saturated conditions throughout the entire simulation period and this is unlikely.

The barrier's failure point in terms of multiples of average precipitation before significant drainage occurs was not investigated in this work and cannot be stated. However, the simulation did include an extended period of above average precipitation. During the period 1960–1965, average annual precipitation rate was approximately 11 inches, while the long-term average for the INEEL is approximately 8.5 inches. During this period, the barrier continued to reduce infiltration over that in the existing soil profiles.

The period over which the cover needs to function is 189 years. During this period, climatic changes are unlikely and the 42-year period of meteorological data should adequately represent conditions at the site.

5.2 Parameterization of Transpiration

The UNSAT-H code requires several parameters to estimate the effect of transpiration. These parameters were based on site-specific data for crested wheatgrass. The crested wheatgrass parameters were the same as those used by Magnuson (1993) with the exception of soil type dependent parameters. Magnuson (1993) simulated two proposed engineered barriers being considered for use in eventual closure of the Subsurface Disposal Area. The soil type dependent parameters were estimated using classical concepts of soil-water availability to plants. The UNSAT-H transpiration parameters used in this study are provided in Table 2.

The maximum root depth for crested wheatgrass can be greater than 220 cm. However, the roots should not penetrate a layer with very low moisture and organic content if there is no water source below. The coarse sand layer in the native soil layered profile and the gravel/cobbles in the capillary barrier cover profile both represent these conditions. For this reason, the simulated maximum root depth was limited to 60 cm in the native soil layered profile and 122 cm in the cover profile. The maximum root depth for the native soil profile was set to 220 cm.

Table 3. Crested wheatgrass transpiration parameters.

Transpiration Parameter	Simulated Value	Source
Growing Season	March 20 to July 15	Magnuson (1993)
Root Length Density (RLD) Function Parameters $RLD = Ae^{-Bz}+C$	A = -0.36 B = 0.04 C = 0.10	Magnuson (1993)
Maximum Root Depth	140 cm	Magnuson (1993)
Wilting Point Head	30,680 cm (30 bars)	Estimated
Slowing Transpiration Head	23,000 cm	Estimated
Anaerobic Head	Silt Clay = 200 cm Sandy Loan = 13.3 cm	Air Entry Head of Soil ($1/\alpha$)
Plant Surface Coverage	35%	Magnuson (1993)
Plant Biomass	220 g/m^2	Magnuson (1993)

6. SIMULATION RESULTS

A summary of average annual water balance totals from 1952 to 1994 for the drainfield cap and the existing soil profiles is presented in Table 4. The simulation results indicate that a soil cover constructed from Rye Grass Flats soil will intercept or divert nearly 100% of total precipitation because of evapotranspiration and run-off. A soil cover constructed with the Lincoln Boulevard Borrow Source soil will intercept approximately 98% of the total precipitation. However, the Lincoln Boulevard Borrow Source soil cover does not rely on run-off to reduce deep percolation and is more conducive for plant growth. The existing soil profile simulation indicates that deep percolation at the CFA-08 drainfield is 4.44 cm/year. This value is higher than the 1-cm/year INEEL average (Cecil et al. 1992), because the soil near the CFA-08 drainfield contains a higher percentage of sand than the average INEEL soil. The native soil layered profile simulations indicate that the natural gravel stratum below the native soil does not significantly affect deep percolation. The average annual percolation rate was approximately 5 cm/year. The contrast in hydraulic behavior between coarse sand and sandy loam is not sufficient for the system to behave as a capillary barrier.

Table 4. Average annual water balance results from the UNSAT-H simulations.

Profile	Precipitation (cm)	Runoff (cm)	Evaporation (cm)	Transpiration (cm)	Drainage (cm)	ET	T/ET
Native Soil	21.9	0.095	10.6	6.85	4.44	17.45	0.39
Layered Native Soil	21.9	0.131	10.4	6.41	5.02	16.81	0.38
Rye Grass Flats Soil Cover	21.9	16.1	4.94	0.972	0.000	5.912	0.16
Lincoln Boulevard Borrow Source Soil Cover	21.9	0.039	14.8	6.81	0.520	21.61	0.32

Transpiration does not represent a large fraction of the total simulated evapotranspiration in the Rye Grass Flats soil barrier profile because of the very fine characteristic of the silty clay soil. The Rye Grass Flats soil has a large fraction of silt and clay, which allows capillarity to easily wick soil moisture back to the surface. The fine nature of the Rye Grass Flats soil also results in a very low hydraulic conductivity and very high air entry potential. The low hydraulic conductivity causes the soil to become saturated after infiltration events, resulting in anaerobic conditions. The high air entry potential results in the 30-bar wilting point to be reached at a higher moisture content than other more loamy soils. The simulated window for plant growth and transpiration is between the air entry matric potential and wilting point matric potential. Both these effects result in a narrow window for plant transpiration. In contrast to the Rye Grass Flats soil barrier profile, transpiration in the existing and Lincoln Boulevard Borrow Source soil profiles represented approximately 40% and 30% of the total evapotranspiration, respectively. This is because the sandy loam and loam soil provides conditions more conducive for plant growth.

The UNSAT-H results also illustrate the effect that the capillary barrier materials have on soil moisture contents. Moisture contents in the sand and gravel remained very low and nearly constant throughout the modeling period, while the moisture contents in the overlying silty clay remained wet, which varied with the seasonal meteorologic conditions near the surface. Moisture content profiles are provided in Figures 2 and 3 to illustrate the soil moisture dynamics occurring in the barrier profiles. The profiles represent spring, summer, fall, and winter soil moisture in the cap and existing soil for a representative year (1981). The year 1981 is illustrated because the total precipitation that occurred during this year approximated the average precipitation over the entire simulation period.

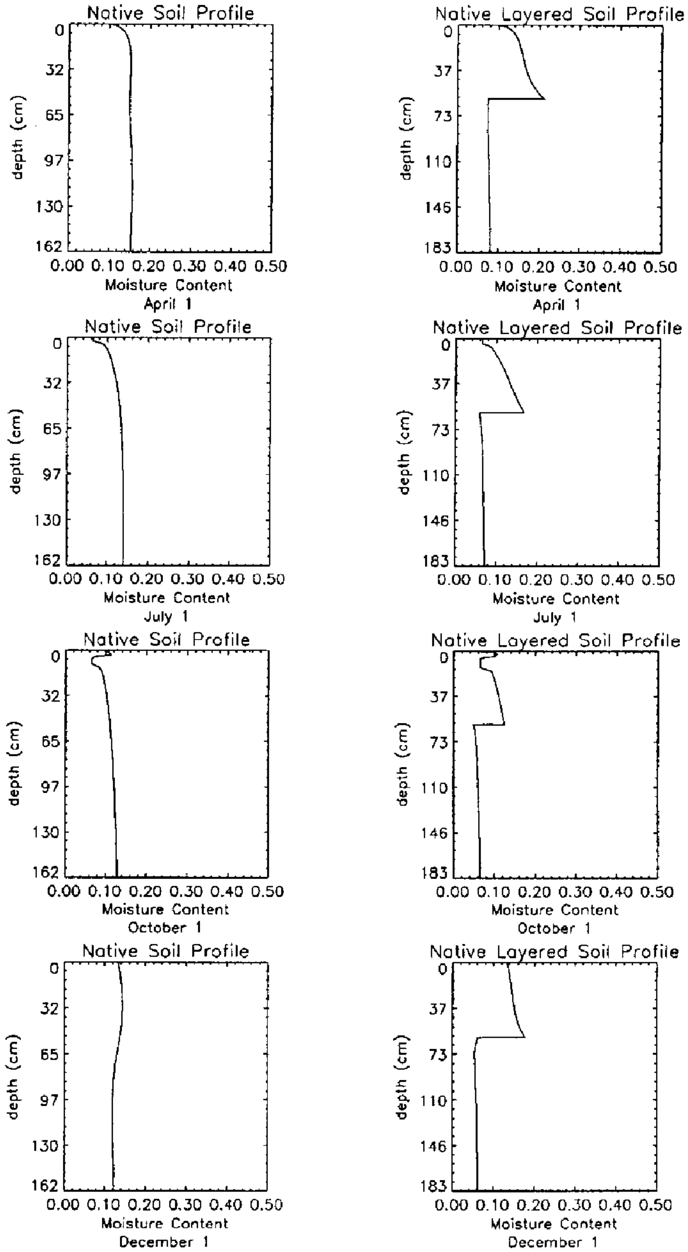

Figure 2. Native soil and layered soil cap moisture content profiles for a representative year (1981).

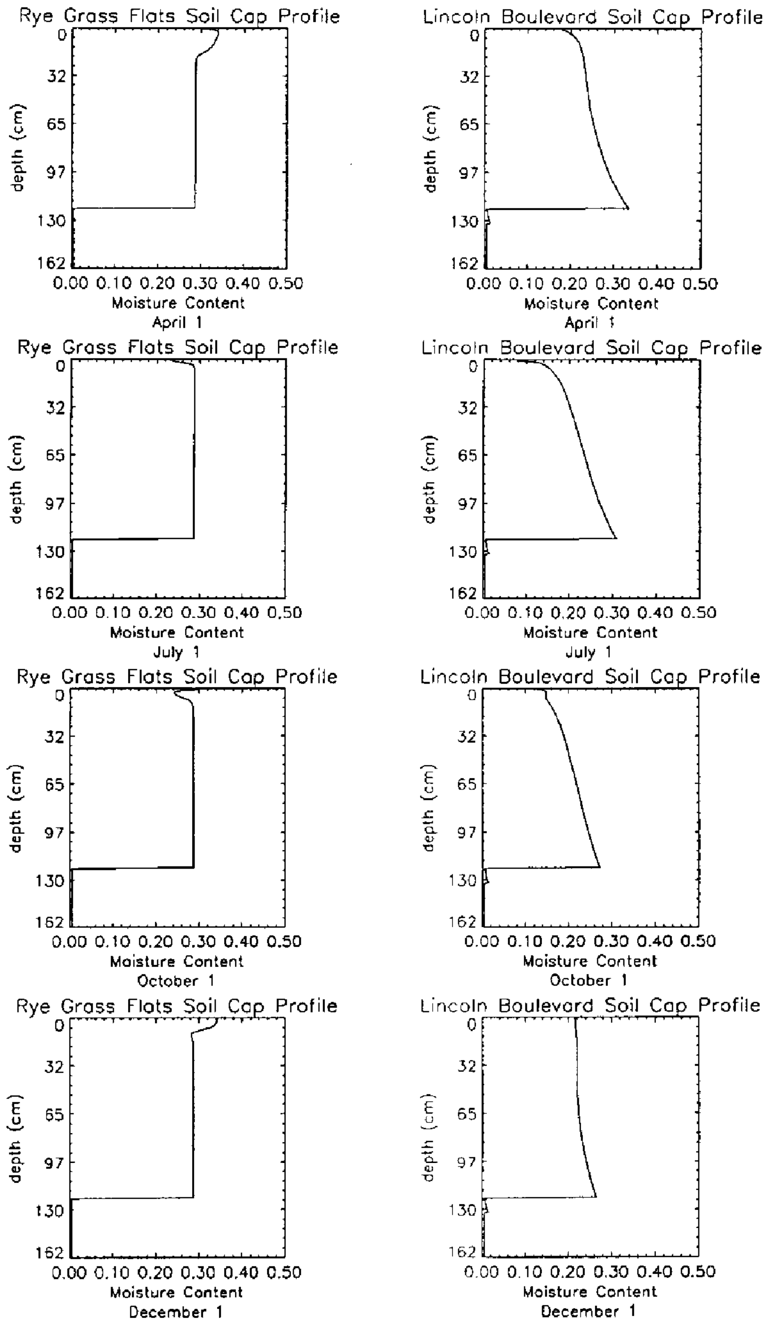

Figure 3. Rye Grass Flats and Lincoln Boulevard Borrow Source soil capillary barrier cap moisture content profile for a representative year (1981).

7. CONCLUSIONS

The results of this study indicate that an engineered capillary barrier cap will significantly reduce deep percolation at the CFA-08 drainfield site from the current amount. The simulations indicate that the aquifer recharge rate (5 cm/year) at the drainfield is greater than the INEEL average (1 cm/year) and placement of a barrier cap will reduce this value to 0.5 cm/year or less. The EDF simulations do not support this observation. All four simulated configurations have plant covers but only the Rye Grass Flats soil cover effectively eliminates deep infiltration.

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